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Ontology for experimentation of human-building interactions using virtual reality

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ABSTRACT

Scientific experiments significantly enhance the understanding of human-building interactions in building and engineering research. Recently, conducting virtual reality (VR) experiments has gained acceptance and popularity as an approach to studying human-building interactions. However, little attention has been given to the standardization of the experimentations. Proper standardization can promote the reusability, replicability, and repeatability of VR experiments and accelerate the maturity of this emerging experimentation method. Responding to such needs, the authors proposed a virtual human-building interaction experimentation ontology (VHBIEO). It is an ontology at the domain level, extending the ontology of scientific experiments (EXPO) to standardize virtual human-building interaction experimentation. It was developed based on state-of-the-art ontology development approaches. Competency questions (CQs) were used to derive requirements and regulate the development. Semantic Web technologies were applied to make VHBIEO machine-readable, accessible, and processable. VHBIEO incorporates an application view (APV) to support the inclusion of unique information for particular applications. The authors performed taxonomy evaluations to assess the consistency, completeness, and redundancy, affirming no occurrence of errors in its structure. Application evaluations were applied for investigating its ability to standardize and support generating of machine-readable, accessible, and processable information. Application evaluations also verified the capability of APV to support the inclusion of unique information.

1. Introduction

Scientific experiments play an important role in discovering knowledge, formulating theories, and creating technologies. In human-building interaction research, they are a core component to enable assessments of the consequence of human-building interactions, such as energy efficiency, building system performance, and occupant health and comfort. Recently, many researchers have turned to virtual reality (VR) as an alternative approach to enhance the capability of human-building interaction experiments [1]. Examples are the use of VR in conducting experiments regarding building system interaction [2,3], occupant comfort [4–6], and human safety and wellbeing [7]. Such studies can improve building performance analysis by analyzing human-building interactions specific to building contexts. The potential is significant because many studies have pointed out that the lack of sufficient account of human-building interactions contributes to the discrepancy between the estimated and actual building performance [8].

The proliferation of using VR in human-building interaction experiments calls for comparability among similar experiments because barriers exist and limit VR-based human-building interaction experiments. The diversity in experimental design in the domain is a crucial barrier. Since individual researchers design their experimentation, design contexts often differ in different experiments, even though they aim to achieve comparative targets (e.g., understanding human-building interactions). Furthermore, researchers use different schemes to manage and store information, which obstructs the experimentation from being shared among researchers. In addition, the use of VR devices may affect the comfort of participants and induce cybersickness [3,9]. The experiments are often performed in a short period of time and typically result in a limited sample size, which may affect the validity and generalizability of experiment results. Therefore, there is a crucial need for standardizing information to reduce impacts of the diversity and assist sharing of experimentation in the virtual human-building interaction research domain [10].

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An ontology is a well-known mechanism to define, capture, and standardize information, and make it explicit for seamless sharing in an area of interest [11]. It is the specification of a conceptualization comprising terms representing concepts and relations representing the interconnectedness of terms. Ontologies have been developed and effectively deployed to support knowledge sharing in various research domains. Lee et al. [12] developed a linked data system framework for sharing construction defect information. The framework used an ontology to extract defect information from BIM models. Kitamura et al. [13] developed SOFAST software, based on an ontological framework of functional design knowledge. It was deployed in a production company, sharing functional design knowledge on production systems. SOFAST enabled the company to elicit knowledge possessed by each designer and share it among team members. IoT-Stream was an ontology for Internet of Things data streams [14]. It supported data streaming in many fields, such as smart healthy living (e.g., smart homes and watches) and smart city traffic (e.g., traffic analysis).

An ontology is based on the description logic that allows machine readability and reasoning on data, which makes ontology more advantageous over other approaches such as taxonomies and rule tags [15]. Such a proven feature benefitted previous research. Ploennings et al. [16] applied the Brick ontology with 220 semantic concepts to map data of six campus buildings with 3,300 sensors, which included a total of 14,830 physical relationships between sensors. The data were computationally accessed and used to train a machine-learning model for detecting and diagnosing building energy and thermal comfort. Delgoshaei et al. [17] proposed an artificial intelligence (AI) algorithm to provide synergic assistance in intelligent building systems. They implemented weather and utility ontologies to standardize online weather and utility-related information. The algorithm integrated the information for training purposes and predicted electricity consumption. There are many other works that used ontologies for supporting machine readability and reasoning data, such as building automation systems [18,19] and building performance measurements [20]. A common theme of the aforementioned publications is ontologies have supported processing machine-readable information with different levels of structural and semantic complexity. Thus, the successful applications of ontologies justify their use for virtual human-building interaction experimentation because machine-readability, accessibility, and processibility play an important role in processing information for building performance analysis and modeling.

The authors developed a virtual human-building interaction experimentation ontology (VHBIEO) to support the standardization of virtual human-building interaction experimentation. Referring to four state-of-the-art ontology development approaches (i.e., ONTOLOGIES [21], METHONTOLOGY [22], Ontology Development 101 [23], and NeOn [24]), the development involves three major steps, initiation, construction, and evaluation. Competency questions (CQs), representations of requirements, are used to regulate the development. Specifically, VHBIEO was developed by extending the ontology of scientific experiments (EXPO) [25] at the domain level and reusing concepts from existing ontologies and semantic models. In addition, many important terms were newly introduced in VHBIEO. Semantic web technologies made VHBIEO machine-readable, accessible, and processable. DOGMA methodology [26] was applied to developing the internal structure of VHBIEO, describing interconnectedness and commitment of terms. Application views (APVs) were applied to allow the inclusion of unique information for applications. Evaluations, including taxonomy and application evaluations, were performed to assess structural errors and ability of VHBIEO.

The main contribution of this research includes (1) providing standardized information for human-building interaction experimentation, (2) enhancing information sharing among researchers in the domain, and (3) enabling the production of machine-readable, accessible, and processable information associated with virtual human-building interaction experimentations. The contribution aims at overcoming barriers caused by the diversity of experimental design and limitations of VR experiments. VHBIEO helps establish consistency in information sharing for the research domain, which potentially accelerates the maturity of this emerging experimentation approach.

2. Procedure to develop VHBIEO

Various state-of-the-art approaches for developing an ontology exist. Among them ONTOLOGIES [21], METHONTOLOGY [22], Ontology Development 101 [23], and NeOn [24] are the common approaches. Many scholars adopted or combined the main features of the approaches to establish their own [27]. Hence, the development of VHBIEO is based on the state-of-the-art approaches.

An advantage of using ONTOLOGIES [22] is that it introduces an important step for initiating key ideas and directions of an ontology, i.e., formulating Competency Questions (CQs). Criteria to formulate CQs rely on the purpose, domain, and scope of an ontology and the requirements of an ontology are elicited through answers of CQs. The development of ontologies can be driven by CQs. For example, Saad et al. [28] used CQs for developing requirements of Solat ontology. Using CQs, they clearly identified the domains and scope of the ontology, consistently maintained ideas, and investigated whether the ontology fitted its purposes throughout the development. Freitas and Vieira [29] developed software performance testing ontology. They formulated CQs to elicit requirements and inferred their answers to define terms, properties, and instances of the ontology. Amorocho and Hartmann [30] developed Reno-Inst ontology by formulating CQs to establish the ontology specifications and identify relevant concepts. The evidence points out that CQs are effective for eliciting requirements of an ontology, including VHBIEO.

Ontology Development 101 [23] recommends reusing, refining, and extending existing ontologies. In addition, NeOn [24] recommends re-engineering and merging existing ontological (e.g., ontologies as a whole, ontology modules, and ontology statements) and non-ontological resources (e.g., semantic models and ontology design patterns). The purpose is to encourage developers to avoid developing an ontology from scratch, reducing development complications and resources.

For constructing an ontology, terms have to be identified and classified into different classes to form an ontology structure [22,23]. The classification consolidates a hierarchically structured set of unambiguously identifiable terms [31]. Consequently, a hierarchical classification is applied to form a structure of VHBIEO.

Ontology development must consider an internal structure of an ontology, namely interconnectedness and commitment of terms, to complete and make an ontology usable [23]. The Developing Ontology-Guided Mediations of Agents (DOGMA) methodology [26] proposed a distinctive method, which clearly distinguishes the internal structure into two layers (i.e., ontology base and ontological commitment). The ontology base establishes interconnectedness of terms and the ontological commitment describes the axiomatization of application information. DOGMA is implemented to construct the internal structure of VHBIEO.

Often, applications include unique information that an ontology does not support. VHBIEO prepares for the inclusion of such information by adopting the concept of Model View Definition (MVD) implemented in Industry Foundation Classes (IFC), allowing end-users to create subsets of IFC schema for describing application-specific information [32]. Subsets can be as broad as nearly an entire schema or as specific as an object type [33]. The authors apply the concept of MVD to create application views (APVs) for allowing the inclusion of unique information for particular applications, which, in addition, contribute to making VHBIEO extensible.

Most ontology developers use ontology editors to not only organize the ontology structure but also scrutinize errors. Among available editors, Protégé [34] is the most popular one, with the major reasons of being open-source software, simple, and easy to use. Its functionality can

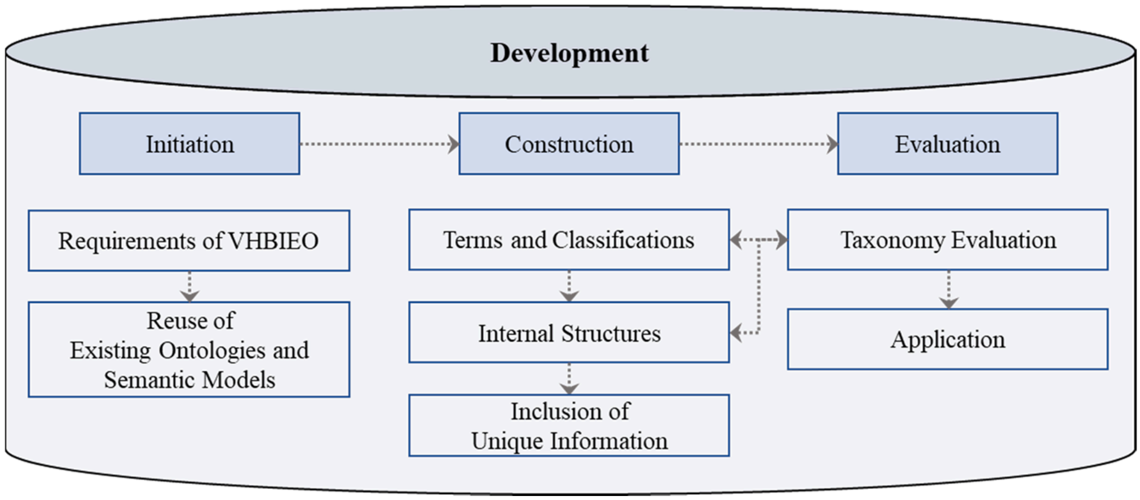

Fig. 1. Procedure to develop VHBIEO.

Table 1
List of CQs.

No.	Competency questions (CQ)
CQ 1	What are stimuli influencing interactions? (Answered in Section 3.2.1.1.2)
CQ 2	What are human-building interactions involved in an experiment? (Answered in Section 3.2.1.1.2)
CQ 3	What is the influence of interactions but not considered stimuli? (Answered in Section 3.2.1.1.2)
CQ 4	What environments are used to conduct an experiment? (Answered in Section 3.2.1.1.3)
CQ 5	What are the building parameters involved in an experiment? (Answered in Section 3.2.1.1.4)
CQ 6	What units are used in an experiment? (Answered in Section 3.2.1.1.5)
CQ 7	What is the plan of an experiment? (Answered in Section 3.2.1.1.6)
CQ 8	What are the devices to observe and collect data? (Answered in Section 3.2.1.2.1)
CQ 9	Who performs interactions? (Answered in Section 3.2.1.2.1)
CQ 10	What tools are used for simulations in an experiment? (Answered in Section 3.2.1.2.2)
CQ 11	What is the interconnectedness of the terms in VHBIEO? (Answered in Section 3.2.2.1)
CQ 12	What are the commitments of the terms in VHBIEO? (Answered in Section 3.2.2.2)
CQ 13	How does VHBIEO allow the inclusion of unique information? (Answered in Section 3.2.3)
CQ 14	How does VHBIEO support machine-readable, accessible, and processable data files? (Answered in Section 3.3.2.2)

be increased by adding plug-in functions and an application programming interface (API). Furthermore, it allows users to use the web ontology language (OWL), which has been endorsed by the World Wide Web Consortium (W3C) as the ontology language of the semantic web [27].

Evaluations aim to quantify that an ontology meets its requirements. METHONTOLOGY [22] suggests looking for taxonomy errors (e.g., inconsistency, incompleteness, and redundancy). NeOn [24] recommends the evaluation of the technical quality of an ontology against applications, and feedback from domain experts, users, ontology developers, and practitioners. As recommended in METHONTOLOGY [22], taxonomy evaluations are used to assess the consistency, completeness, and redundancy of VHBIEO during construction. After the construction, the technical quality evaluations take place by following suggestions in NeOn [24].

In summary, ontology development can be generalized into three major stages, namely initiation, construction, and evaluation. The initiation comprises (1) establishing ontology requirements, and (2) considering reusing, extending, merging, refining, and re-engineering existing ontological and non-ontological resources. The construction involves (1) identifying relevant terms, (2) constructing an internal structure of an ontology, namely interconnectedness and commitment of terms, and (3) providing features to include unique information that an ontology may not support. The evaluation covers (1) evaluation during construction, checking for taxonomy errors to justify whether an ontology involves internal errors related to its structures and prevent the occurrence of logical conflicts, and (2) evaluation after construction, testing an ontology against applications, and feedbacks from domain experts, users, ontology developers, and practitioners to appraise its quality and confirm its ability. Accordingly, the procedure for developing VHBIEO is formed and illustrated in Fig. 1. Protégé, an ontology editor, is the main tool to support the development of VHBIEO.

3. Development

3.1. Initiation

3.1.1. Requirements of VHBIEO

According to the procedure to develop VHBIEO, CQs are formulated to elicit requirements of VHBIEO. The formulation of CQs relies on the contribution, identifying the purpose, domain, and scope, and crucial needs for developing an ontology discussed in Section 2. Afterward, CQs were referred and answered, when discussing the specifications of VHBIEO. All CQs are listed in Table 1. The following discusses and clarifies the details of formulating CQs.

3.1.1.1. VHBIEO must provide terms describing aspects regarding virtual human-building interaction experimentation. Referring to best practices and lessons learned from published VR-based experiments on human-building interactions [35–39], the authors encapsulated core aspects regarding virtual human-building interaction experimentation as fundamental elements, experimental plans, data collection, and equipment.

The fundamental elements refer to elements that play a role in establishing experiments. They comprise experimental variables (formulation of CQ 1 – 3), experimental settings (formulation of CQ 4), building parameters (formulation of CQ 5), and uits of measurement (formulation of CQ 6). Variables are the primary elements that involve in experiments. There can be various types of variables, such as independent variables (e.g., stimuli influencing actions), dependent variables (e.g., occupant behaviors and actions), and contextual variables (e.g., the outdoor temperature that is not considered in the experiments; however, they may influence actions). The experiments may perform in virtual reality (VR) and in-situ environments, where experimental settings enable the control of the environments. For instance, the virtual setting enables the control of virtual environments. Buildings are the main part of experiments, where their configurations (e.g., dimensions, sizes, components, materials) and systems (e.g., lighting and HVAC) need to be considered in the experiments. After all, units of measurement must be identified to describe experimental measurements.

Experimental plans organize the fundamental elements. For instance, a plan defines the controlled conditions of independent variables (e.g., a range of work area illuminance), actions (e.g., a light switch can be turned on, off, and dim), and sequence of events (e.g., sequence of the time in a day). In addition, a plan may incorporate principles and considerations specifically for an experiment, which helps to establish its operational procedure. CQ 7 elicits the requirement of the experimental plan.

Data collection refers to procedures to observe the experiments and collect results. It describes which variables are observed and how to observe and collect information. It includes an explanation of observing devices (e.g., actuators, sensors, and questionnaires) and organizing information (e.g., identification of participants and storing data). CQ 8 – 9 represent requirements associated with data collection in VHBIEO.

The experiments commonly require advanced simulation technology such as VR equipment (e.g., HTC Vive, Meta Quest, and Microsoft HoloLens) [40], thermal-controlled environments (e.g., advanced HVAC and climate chamber) [41], and simulation software (e.g., 3dsMax, UE4, and Unity) [42]. Such information can be described as simulation equipment contributing to formulating CQ 10.

3.1.1.2. VHBIEO must explicate its internal structure. The internal structure accounts for the interconnectedness and commitments of terms that conform to the contributions of VHBIEO. Similar to other ontologies, interconnectedness has to be defined to express relationships between terms in VHBIEO. It describes the roles and properties of terms that affect their connected terms. For example, the connection between a variable and a unit is defined by “has”. Such a relationship allows users and machines to understand and correctly query relevant information. Accordingly, CQ 11 is formulated to elicit the requirement of interconnectedness in VHBIEO.

Commitments refer to groups of terms and their interconnectedness that may be applied to specific applications. Each commitment contains consistent constraints that belong to a particular application. For instance, one of the commitments in VHBIEO is virtual commitment. It is a group of terms that only describe VR realated components in experiments, such as virtual reality hardware, virtual setting, and virtual actuators. If an experiment is performed solely in VR, only the virtual commitment is needed to develop the schema and data file of experimentations without having to explore all terms in VHBIEO. Commitments benefit information sharing because they potentially minimize time, effort, and computational resources to create application-specific schemas and data files. CQ 12 is formulated to explicate requirements relevant to the commitments in VHBIEO.

3.1.1.3. VHBIEO must assist in the inclusion of unique information regarding particular experiments. VHBIEO must have the ability to assist customization for including unique information used by particular applications. CQ 13 represents requirements for realizing this objective.

3.1.1.4. VHBIEO must promote machine-readable, accessible, and processable data files associated with virtual human-building interaction experimentation. The associated CQ is CQ 14, representing requirements addressing how VHBIEO promotes machine-readable, accessible, and processable data files.

3.1.2. Reuse of existing ontologies and semantic models

A previous study proposes the structure of virtual human-building interaction experiments genetically called spatial–temporal event-driven modeling (STED) [43], which provides a foundation for describing virtual human-building interaction experiments. Several studies have successfully applied STED to model their experiments, such as [44,45], and [46]. STED models the experiments as a series of events. At a given time, the condition of a virtual experiment can be defined by *State* which is “the collective status of operations in different building spaces at a certain point of time, especially the conditions of building systems and components that are operable by humans” [43]. The status of operations refers to simulated conditions in an experiment, such as lighting or noise simulation and contextual information. The contextual information, called *Context* in STED, includes “situational factors associated with a building” [43]. An example of contextual information is when studying the indoor illuminance level in a work area, one may also specify the day and time of outdoor conditions, such as 8:00 am on a typical summer day. A context may change due to the occurrence of *Event*, which refers to an intended intervention in a virtual experiment; for example, the change of the simulated illuminance level in the work area, the elapse of simulated time, and the adjustment of ambient temperature. An event may cause perceived discomfort to occupants and further lead to their need for adjustments. Consequently, the *H-B Interaction* (i.e., human-building interaction) in STED represents their intention to mitigate discomfort, such as turning on lights when the simulated work area illuminance is low. In summary, STED uses *State*, *Event*, *Context*, and *H-B Interaction* as keys to model virtual experiments. Therefore, the authors took those keys as core terms of VHBIEO to describe concepts of virtual human-building interactions.

Many ontologies and semantic models provide terms acceptably used in general. It is helpful and practical to consider inheriting and reusing such terms to develop VHBIEO. Since VHBIEO is a domain ontology for scientific experimentation, inheriting and extending concepts of general scientific experiment ontology is ideal. An upper-level scientific experiment ontology exists, which is the ontology of scientific experiments (EXPO) [25]. Its purpose is to support the standardization of information in scientific experimentation. It provides over 200 terms. Many domain-specific ontologies have been developed by extending EXPO, such as microarray gene expression society ontology (MO) [47], metabolomics standards initiative (MSI) ontology [48], and functional genomics investigation ontology (FuGO) [49], which evidently prove that EXPO is acceptable among scientific experiment domains. As such, the authors decided to develop VHBIEO by inheriting and extending EXPO.

VHBIEO relies on other concepts associated with the experimentations, such as occupant behaviors, buildings, observations, and units. Various ontologies and semantic models can be reused, namely, the ontology to represent energy-related occupant behavior in buildings (DNAs) [50,51], ifcOWL ontology [52], the semantic sensor network ontology (SSN) [53], the survey ontology (SUR) [54], and the units of measurement ontology (UO) [55].

Concepts related to the building’s occupants and their behaviors are captured using the drivers, needs, actions, and systems (DNAs) framework [50]. With DNAs, descriptions of occupant behavior with building simulation become possible in VHBIEO.

The Industry Foundation Classes (IFC) is a standardized digital description of the built environment, such as buildings and civil infrastructure, organized by buildingSMART international organization. It becomes an international standard (ISO 16739–1:2018) that has been used across building-related hardware devices, software platforms, and interfaces. It provides conceptual data schema and an exchange file format for building-related information represented as an EXPRESS schema [56]. ifcOWL ontology is developed by directly converting the EXPRESS schema, providing over 1,230 concepts related to different aspects of buildings, such as concepts related to building, space, zone, and energy [57]. It opens an opportunity for VHBIEO to reuse concepts relevant to building.

Since sensors are commonly used in experiments, the semantic sensor network (SSN) ontology is referenced [53]. SSN is built on SOSA

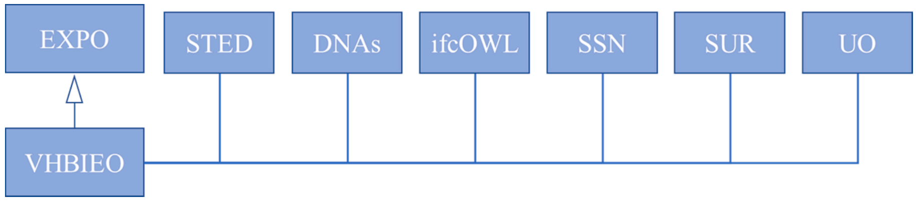

Fig. 2. Reused existing ontologies and semantic models in VHBIEO.

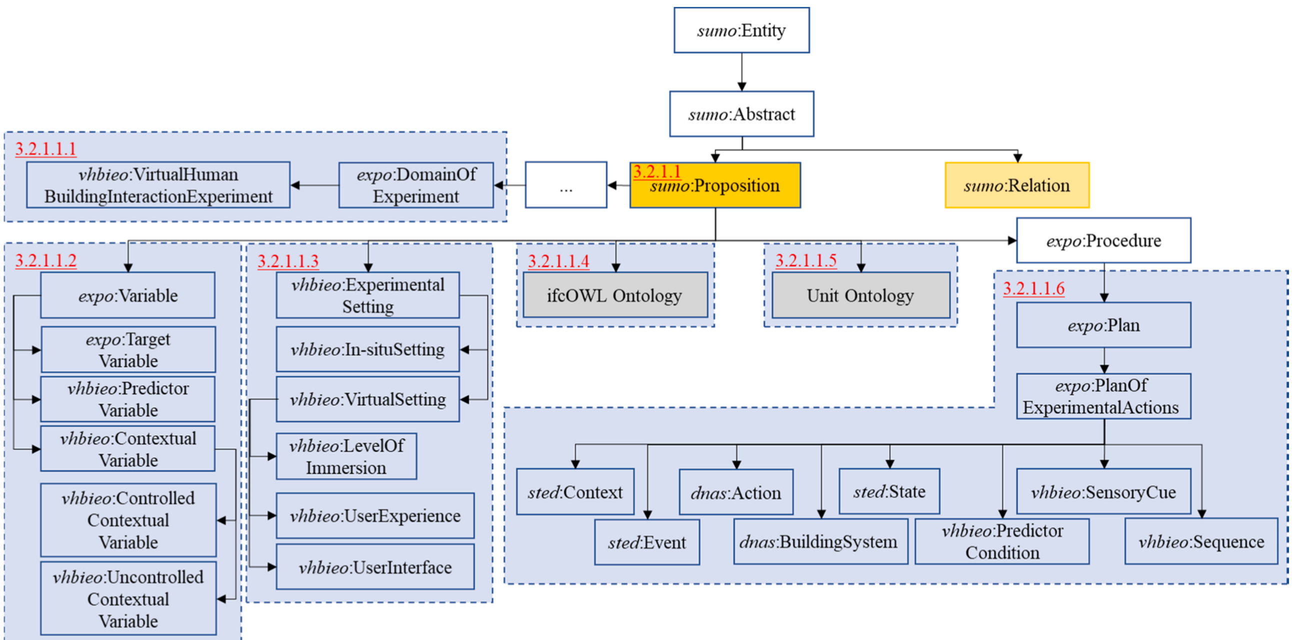

Fig. 3. The classification of terms in the VHBIEO (*sumo*:Proposition).

core ontology (Sensor, Observation, Sample, and Actuator). SSN describes how to carry out observations and collect samples in experiments [58]. Moreover, surveys have been used to collect data in virtual human-building interaction experiments. They capture factors related to occupants, such as backgrounds and perspectives (e.g., demographic and psychological factors). Surveys consist questions and answers, where various question and answer types can co-exist. The survey ontology (SUR) [54] allows users to form an infinite number of surveys through combinations of questions and answers. As a result, SSN and SUR are reused to describe information observation and collection in VHBIEO.

Units play a vital role in standardizing and formalizing experimentations. Units support information interoperability and semantic information sharing among diverse experiments. The units of measurement ontology (UO) [55] provides terms and definitions of various units of scientific measurement, many of which can be reused in VHBIEO.

Fig. 2 summarizes the reused existing ontologies and semantic models for developing VHBIEO.

3.2. Construction

3.2.1. Terms and classification

The resources defined in VHBIEO are publicly available through Uniform Resource Locator (URL) as https://w3id.org/vhbieo. Terms defined in VHBIEO are individually addressable via a unique Uniform Resource Identifier (URI) as https://w3id.org/vhbieo#term. In the following sections, namespace prefixes are used to represent the origin of terms; *vhbieo*, *expo*, *sted*, *dnas*, *ifc*, *ssn*, *sur*, and *uo* represent VHBIEO, EXPO, STED, DNAs, ifcOWL, SSN, SUR, and UO, respectively. It must be noted that many terms reused from EXPO use *sumo* as the prefix rather than *expo* because EXPO reuses such terms originated in the Suggested Upper Merged Ontology (SUMO). Similar cases occur with reusing terms in the SSN, where *sosa* is used rather than *ssn*. Additionally, the authors use Protégé, an ontology editor, to assist the development.

The classification of terms and the extension to EXPO are determined according to EXPO's concepts and structure to ensure the appropriateness, completeness, and effectiveness of VHBIEO. Accordingly, terms in VHBIEO are classified under '*sumo*:Proposition' and '*sumo*:Relation'.

3.2.1.1. 'sumo:Proposition'. '*sumo*:Proposition' is "an abstract entity that expresses a complete thought or a set of such thoughts" [25]. VHBIEO reuses some terms that are subclasses of '*sumo*:Proposition', namely '*expo*:DomainOfExperiment', '*expo*:Variable' and '*expo*:Plan'; additionally, '*vhbieo*:VirtualHumanBuildingInteractionExperiment', '*vhbieo*:ExperimentalSetting', ifcOWL ontology and Unit ontology are extended to '*sumo*:Proposition' (Fig. 3).

3.2.1.1.1. 'expo:DomainOfExperiment'. According to EXPO, '*expo*:DomainOfExperiment' is "a field of study in which an experiment is designed to discover new knowledge" [25], providing an opportunity to introduce '*vhbieo*:VirtualHumanBuildingInteractionExperiment' describing the domain of experiments studying virtual human-building interactions.

3.2.1.1.2. 'expo:Variable' (Answer to CQ 1 – 3). In addition to existing terms under '*expo*:Variable', VHBIEO introduces two additional terms, '*vhbieo*:PredictorVariable' and '*vhbieo*:ContextualVariable'.

'*expo*:TargetVariable' is a dependent variable, which an experiment uses to discover new knowledge. '*vhbieo*:PredictorVariable' describes an independent variable. '*vhbieo*:ContextualVariable' is a type of variable modeling the context that may affect independent variables or outcomes

Table 2
Terms and conceptual definitions extending '*vhbieo*:ExperimentalSetting'.

Term	Description
vhbieo:In-situSetting	Formation of a real environment contributing to achieving the objectives of a virtual building experiment. Examples are a thermal, lighting, and acoustic-controlled environments.
vhbieo: VirtualSetting	Formation of a virtual environment.
vhbieo:LevelOf Immersion	The sense of immersion such as a non-immersive, semi-immersive, and fully immersive virtual environment [10].
vhbieo: UserExperience	Design of virtual environments that creates experiences in a way that participants are immersed, satisfied, and, consequently, fulfilling experimental objectives [60].
vhbieo: UserInterface	Visual and properties of virtual environments such as colors, typography, buttons functions and interactions, animations, etc. [60]

of an experiment. A contextual variable is neither a predictor nor a target variable, and is either controlled or uncontrolled in an experiment [8]. A controlled contextual variable refers to a variable that is controlled in an experiment. An uncontrolled contextual variable refers to a contextual variable that is assumed not to affect experimental results [59]. Therefore, '*vhbieo*:ControlledContextualVariable' and '*vhbieo*: UnControlledContextualVariable' are introduced as subclasses of '*vhbieo*:ContextualVariable'.

3.2.1.1.3. 'vhbieo:ExperimentalSetting' (Answer to CQ 4). '*vhbieo*: ExperimentalSetting' defines the formation of an experimental environment. Certainly, a virtual environment is a vital setting required in experiments. In many studies, experiments in a real environment are performed alongside the virtual counterpart for several purposes (e.g., guidance, comparison, and validation). Accordingly, two types of environmental settings are included as the subclasses of '*vhbieo*:ExperimentalSetting', namely '*vhbieo*:In-situSetting' and '*vhbieo*:VirtualSetting'. Furthermore, '*vhbieo*:VirtualSetting' opens descriptions of terms relevant to environment as its subclasses, namely level of immersion and usability (i.e., user experience and user interface) [10]. The descriptions of terms are shown in Table 2.

3.2.1.1.4. ifcOWL ontology (Answer to CQ 5). Terms related to building parameters are essential in virtual human-building interaction experimentations. VHBIEO reuses building-related concepts defined in ifcOWL ontology (e.g., building component, material, and property). The terms related to buildings can be retrieved in [52], and the description of terms can be referred in [61]. Examples of terms commonly reused in virtual human-building interaction experimentations are (1) *ifc*:IfcBuilding describes concepts of elements within the spatial structure hierarchy for the components of a building project (together with site, storey, and space), (2) *ifc*:IfcBuildingElement describes all elements that are primarily part of the construction of a building, i.e., its structural and space separating system, and (3) *ifc*: IfcPhysicalSimpleQuantity holds a concept of a single quantity measure value (e.g., area, height, length, width).

3.2.1.1.5. Unit ontology (Answer to CQ 6). VHBIEO reuses terms defined by the units of measurement ontology (UO) [55]. It provides units applied in several scientific experiments. Examples of units relevant to virtual human-building interaction experimentations are '*uo*: area_unit' describing the concept of the unit for an area, '*uo*:light_unit' describing the concept of the unit for lighting (e.g., illuminance, irradiance, and luminance units), and '*uo*:temperature_unit' describing the concept of the unit for temperature.

3.2.1.1.6. 'expo:Plan' (Answer to CQ 7). '*expo*:Plan' has its direct subclass '*expo*:PlanOfExperimentalActions', which is "a specification of a sequence of processes, which is intended to satisfy a specified purpose at some future time" [25].

VHBIEO extended the '*expo*:PlanOfExperimentalActions' to describe the experimental procedure. The procedure is structured based on the key concepts proposed in STED. STED uses contexts (*sted*:Context) to describe situations of contextual variables. VHBIEO defines *vhbieo*: PredictorCondition to describe conditions of predictor variables. In general, combinations of contexts and predictor conditions generate events described by *sted*:Event. It represents experimental scenarios to trigger participant actions (*dnas*:Action). *dnas*:Action describes actions that participants are allowed to perform, which, in the other words, are possible behaviors defined in experiments. Actions may change the state (*sted*:State) of building interactable systems (*dnas*:BuildingSystem). Executed actions are captured and stored in *expo*:ComputationalData, which is explained in the section 3.2.1.2.1. Additionally, VHBIEO describes sensory cues (*vhbieo*:SensoryCue) that are often used for indicating signal or stimulus to guide participants for being interested in perceiving building systems, and events. VHBIEO, further, provides *vhbieo*:Sequence to describe sequential or time-series events. Table 3 elaborates the terms extending '*expo*:PlanOfExperimentalActions'.

Table 3
Terms and conceptual definitions extending '*expo*:PlanOfExperimentalActions'.

Term	Description
dnas:BuildingSystem	Equipment or mechanisms, which a participant may interact with to restore comfort or satisfaction with their environment [50,51]. It describes specific functions of interactable systems that intend to be interacted with by participants in experiments.
sted:State	Collective status of operations in different building spaces at a certain point of time, especially the conditions of building systems and components that are operable by human beings and have energy efficiency consequences [43]. For instance, states of a light switch can be on, dim, and off.
sted:Context	Situational factors associated with and describing situations of a contextual variable [43].
sted:Event	Occurrence that triggers the change of a state or sets the foundation for future events to change a state [43]. It intuitively describes scenarios in an experiment.
dnas:Action	Human interactions with systems or activities that a participant can conduct in order to satisfy their needs. The violation of one or more of the participant's needs leads to discomfort. Therefore, this uncomfortable state for the participant will provoke action. The action may be an interaction with a system in which the participant conjectures that their action will restore comfort [50,51].
vhbieo: PredictorCondition	Controlled conditions of a predictor variable. For example, if the room temperature is a predictor variable, a controlled condition is when the room temperature is at 80-degree Fahrenheit.
vhbieo:SensoryCue	Organization of the data present in the signal, which allows for meaningful extrapolation. For example, sensory cues include visual cues, auditory cues, haptic cues, olfactory cues, and environmental cues.
vhbieo:Sequence	An enumerated collection of events in which repetitions are allowed and order matters.

3.2.1.2. 'sumo:Relation'. *sumo*:Relation has a subclass, '*expo*:Predicate', which has two subclasses, '*expo*:ComputationalData' and '*expo*:Hardware'. These two subclasses allow VHBIEO to extend EXPO for describing experimental data, data collections, and hardware used in the experimentations (Fig. 4).

3.2.1.2.1. 'expo:ComputationalData' (Answer to CQ 8 – 9). EXPO defines '*expo*:ComputationalData' as "experimental observations represented in a form suitable for processing by computer", which contributes to handling description of experimental data and data collection. In virtual human-building interaction experimentations, data collection is generally performed using sensing elements (e.g., sensors and actuators) and surveys. Thereby, the term '*vhbieo*:DataSource' extends to '*expo*: ComputationalData' for describing sensing elements and surveys. Table 4 elaborates on terms extending '*expo*:ComputationalData' and their descriptions.

3.2.1.2.2. 'expo:Hardware' (Answer to CQ 10). EXPO provides '*expo*: Hardware' to support descriptions of hardware used to simulate experimental environments. According to the Merriam-Webster dictionary,

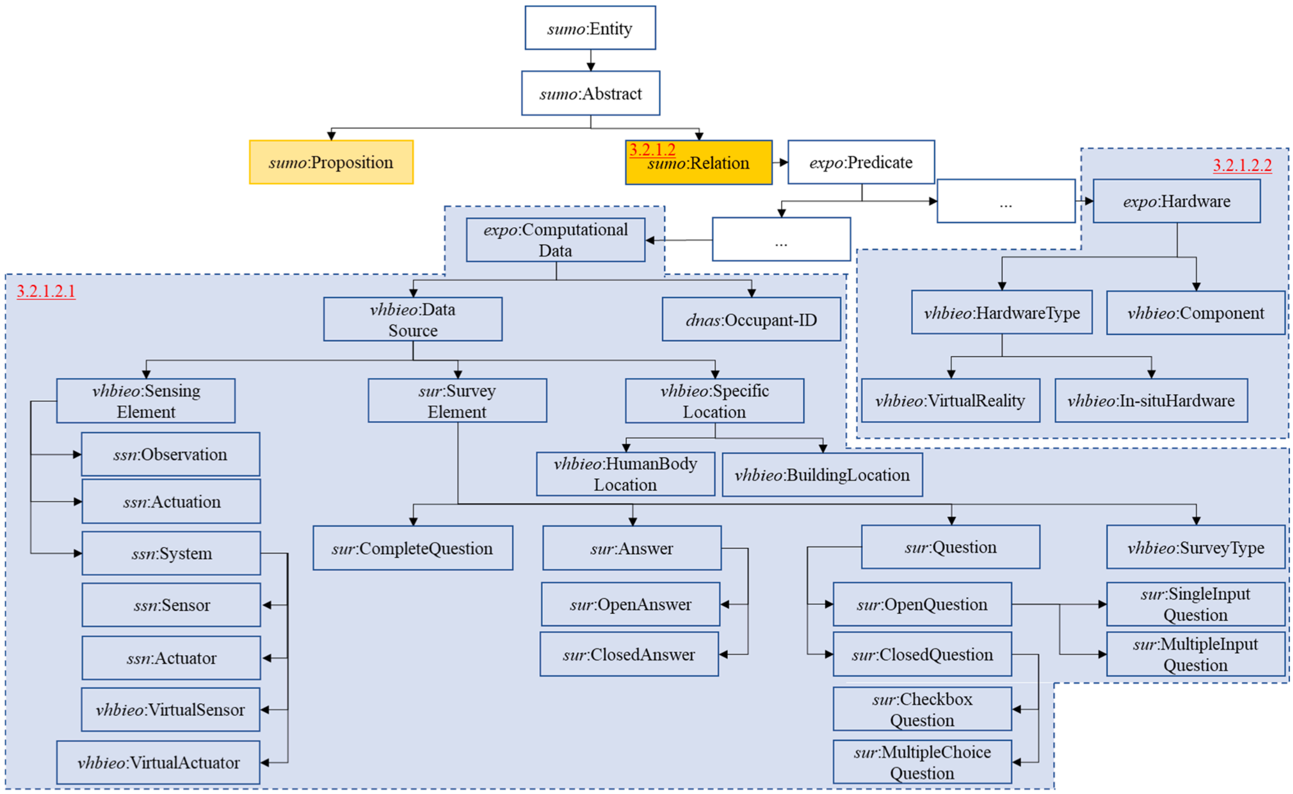

Fig. 4. The classification of classes introduced in the VHBIEO (*sumo*:Relation).

Table 4
Terms and conceptual definitions extending to '*expo*:ComputationalData'.

Term	Description
vhbieo:DataSource	The place, location, or system that collects and holds data in an experiment.
vhbieo:SensingElement	Element that responds to a signal or stimulus and detects events or changes in an environment.
ssn:Observation	"Act of carrying out an Observation or a Procedure to estimate or calculate the value of a property (of a feature of interest). Links to a Sensor describe what made the Observation and how; links to an observable property describe what the result is an estimate of, and to a feature of interest to detail what that property was associated with" [62,58].
ssn:Actuation	"An Actuation carries out an (Actuation) Procedure to change the state of the world using an Actuator" [62,58].
ssn:System	"A unit of abstraction for pieces of infrastructure that implement Procedures. A System may have components, its subsystems, which are other Systems" [62,58].
ssn:Sensor	"Device, agent (including humans), or software (simulation) involved in, or implementing, a Procedure. Sensors respond to a Stimulus, e.g., a change in the environment, or Input data composed from the Results of prior observations and generate a Result. Sensors can be hosted by Platforms" [62,58].
ssn:Actuator	"A device that is used by, or implements, an (Actuation) Procedure that changes the state of the world" [62,58].
vhbieo:VirtualSensor	It is similar to '*ssn*:Sensor', but a sensor is deployed only in IVE.
vhbieo:VirtualActuator	It is similar to '*ssn*:Actuator', but an actuator is deployed only in IVE.
sur:SurveyElement	"An element of a survey procedure" [54].
vhbieo:SurveyType	It refers to a classification of a survey and a corresponding question. In general, the classification is based on the purposes of such a survey. A demographic survey is one of the common survey types.
sur:CompleteQuestion	"Answer provided by a participant in completing a survey for a specific question" [54].
sur:Answer	"An available answer for a survey question" [54].
sur:OpenAnswer	"An open answer for a survey open-ended question" [54].
sur:ClosedAnswer	"An available closed answer for a survey question" [54].
sur:Question	"A question requiring an input from the participant in a survey" [54].
sur:OpenQuestion	"An open-ended question in a survey" [54].
sur:SingleInputQuestion	"An open-ended answer expecting a single input from the participant" [54].
sur: MultipleInputQuestion	"An open-ended answer allowing multiple inputs from the participant" [54].
sur:ClosedQuestion	"A question in a survey with a defined set of available answers" [54].
sur:CheckboxQuestion	"A question having a limited set of potential answers and allowing the participant to select more than one answer" [54].
sur:MultipleChoice Question	"A question having a limited set of potential answers and allowing the participant to select only one answer" [54].
vhbieo:SpecificLocation	Placement or location of a sensor or actuator. It is also used to describe a location that a questionnaire is specific for. VHBIEO provides two children of "*vhbieo*:SpecificLocation", namely "*vhbieo*:HumanBodyLocation" and "*vhbieo*:BuildingLocation" to describe specific locations on the human body (e.g., arms, legs, and faces) and building (e.g., building elements and environments).
dnas:Occupant-ID	Identity of a participant [51,50].

Table 5
Terms and conceptual definitions extended to '*expo*:Hardware'.

Term	Description
vhbieo: HardwareType	Hardware involved in an experiment for simulation purposes. To specifically describe hardware, two subclasses are assigned according to two major simulated environments, namely "*vhbieo*:VirtualReality" and "*vhbieo*:In-situHardware". For instance, "*vhbieo*:VirtualReality" can be used to describe hardware related to virtual reality. Another example is that "*vhbieo*:In-situHardware" can be used to describe hardware to simulate thermal sensation in an in-situ environment.
vhbieo:Component	Corresponding devices, tools, and software used to support simulations.

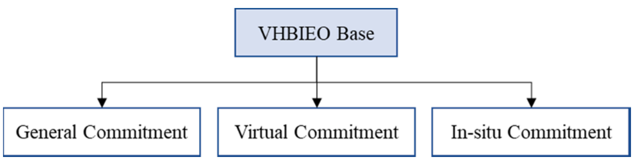

Fig. 5. Ontological commitments in VHBIEO.

hardware is an apparatus used for a particular purpose. Consequently, '*expo*:Hardware' is taken as a placeholder for VHBIEO to include terms related to hardware used in virtual human-building interaction experiments. Terms extending '*expo*:Hardware' comprise '*vhbieo*:HardwareType' and '*vhbieo*:Component'. To allow description of hardware type, '*vhbieo*:HardwareType' contains terms referring to virtual reality (i.e., '*vhbieo*:VirtualReality') and in-situ hardware (i.e., '*vhbieo*:In-situHardware'). Additionally, '*vhbieo*:Component' describes specific components of the hardware. Table 5 demonstrates the terms and their descriptions.

3.2.2. Internal structures

The authors follow the DOGMA methodology [26] to design the internal structure of VHBIEO. It has two main layers, including an ontology base and an ontological commitment to describe the interconnectedness and commitment of terms, respectively.

3.2.2.1. Ontology base (Answer to CQ 11). The ontology base is a context-specific conceptualization of a domain. It explains the interconnectedness of terms using a set of context-specific 'representation-less' binary fact types called "Lexon". A Lexon is represented in a 4-tuple of the form,

<Term1, Role, InverseRole, Term2>

where, *Term1* and *Term2* refer to terms in an ontology.

Role and *InvRole* describe the role and the inverse role of *Term1* and *Term2*.

For example, a Lexon may be expressed as <'*expo*:Variable', '*vhbieo*:hasUnitOf', '*uo*:is_unit_of', '*uo*:Unit'>. Nonetheless, there is an exception for practical purposes, in which DOGMA requires at least one role (i.e., either *role* or *inverse role*) to be present in a Lexon. For instance, a Lexon can be <'*sted*:State', '*vhbieo*:grant', -, '*dnas*:Action'>.

In VHBIEO, terms have been defined in previous sections. Roles and InverseRoles are either reused from existing ontologies or newly created. The former has a prefix representing a reused source of roles. For example, '*ssn*:madeObservation' represents the role "make observation" originated in '*ssn*'. The latter uses '*vhbieo*' as the prefix of roles such as '*vhbieo*:grant'.

3.2.2.2. Ontological commitment (Answer to CQ 12). The ontological commitment organizes groups of Lexons to support specific applications. There can be several commitments, each of which is a set of rules ontologically committing to the constraints of a particular aspect of an application. Since the scope of VHBIEO covers virtual experiments of human-building interaction, its ontological commitment is structured based on the main aspects of the experimentation, namely general, virtual, and in-situ commitments (Fig. 5).

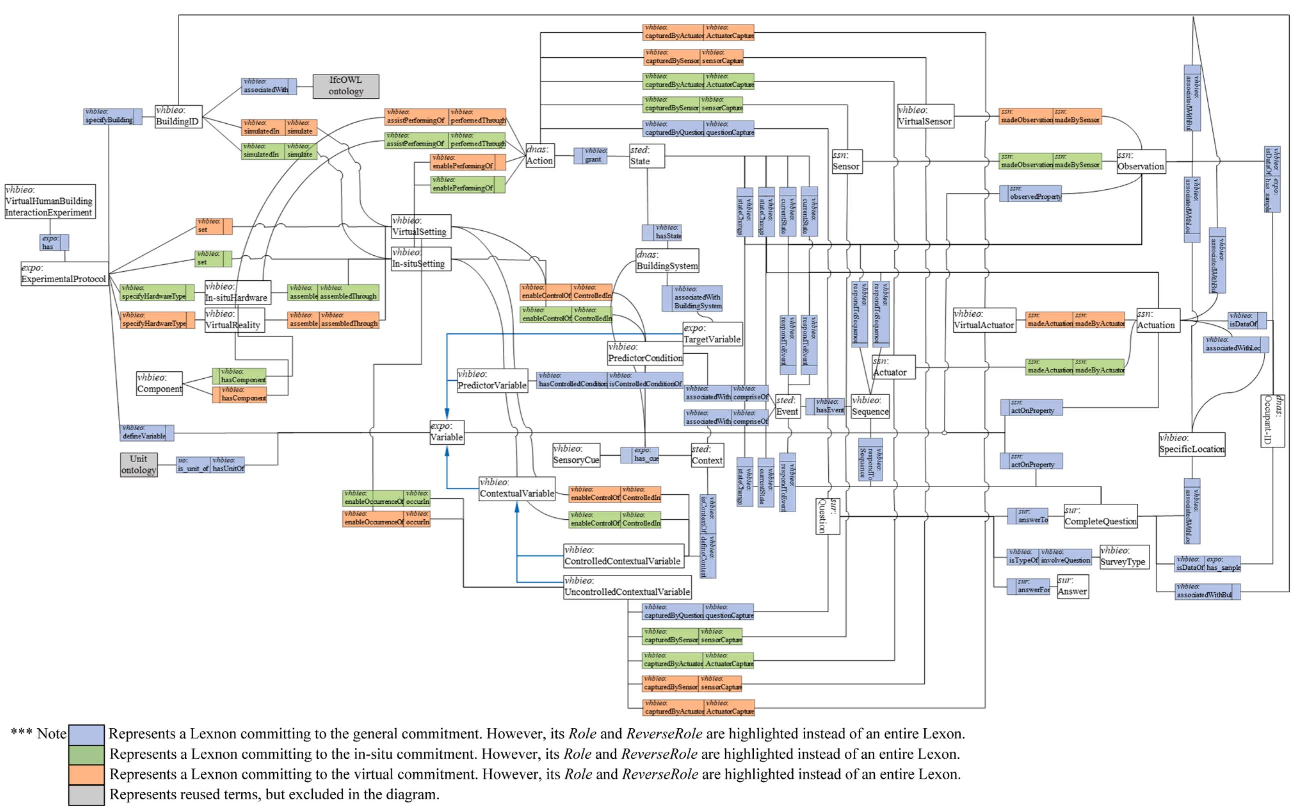

Fig. 6. Diagram of Lexons and commitments of VHBIEO.

The general commitment groups Lexons and provides rules that comply with overall virtual human-building interaction experiments and consent to neither virtual nor in-situ environments. For instance, <‘*vhbieo*:VirtualBuildingExperiment’, ‘*expo*:has’, -, ‘*expo*:ExperimentalProtocol’> is in the general commitment since it does not consent to both virtual and in-situ environments.

The virtual commitment includes Lexons and rules only complying with the contexts of IVE. For example, <‘*vhbieo*:VirtualSensor’, ‘*ssn*:madeObservation’, ‘*ssn*:madeBySensor’, ‘*ssn*:Observation’> belongs to the virtual commitment since all virtual sensors can only be placed and observe human-building interactions in virtual environments.

The in-situ commitment only includes Lexons and rules complying with the contexts of an in-situ environment (i.e., a real environment). For example, <‘*ssn*:Sensor’, ‘*ssn*:madeObservation’, ‘*ssn*:madeBySensor’, ‘*ssn*:Observation’> belongs to the in-situ commitment because all actual sensors can only be placed and observe human-building interactions in in-situ environments.

To further elaborate, examples of virtual human-building interaction experiments are given in the following. Research studies that may apply the general and virtual commitments include experiments performed in [59,63,64], which are experiments to study occupant lighting behaviors in IVEs. An example of a research study that may use all commitments is the experiment reported in [43,65], where the experiment was performed in both IVE and in-situ environments to validate the efficacy of an IVE against thermal-driven behaviors.

Rules associated with each commitment are established based on specific information of the virtual human-building experimentation, including 1) information that is related to the experiments, such as occupant-related data (e.g., demographic information, human body information, and actions); 2) general requirements to complete the experiments such as the experiments must include at least one predictor variable and one target variable; and 3) formalization of values and data used in the experiment such as data formats, e.g., string, integer, or float.

According to the ontology commitments, Lexons are grouped based on the three categories (i.e., general, in-situ, and virtual commitments), and rules are established as described in Appendix 1.

The complete diagram of Lexons and commitments of VHBIEO is presented in Fig. 6.

3.2.3. *Inclusion of unique information (Answer to CQ 13)*

Often, applications do not exactly follow what is provided in an ontology and requires particular customizations. VHBIEO proposes an application view (APV) approach to allow users to incorporate desired terms and structures into VHBIEO for specific usage. For instance, VHBIEO describes *sur*:ClosedAnswer as a subclass of *sur*:Answer. If a 7-point Likert scale is used as one type of the closed answer in an application, users may apply APV to include the Likert scale as a subclass of *sur*:ClosedAnswer.

3.3. *Evaluation*

The evaluation was performed to assess the taxonomy and ability of VHBIEO. During the construction, the taxonomy evaluation was performed to evaluate the consistency, completeness, and redundancy in VHBIEO [22]. After the construction, the application evaluation proved the ability of VHBIEO to describe experimentations and support generating of machine-readable, accessible, and processable data files.

3.3.1. *Taxonomy evaluation*

3.3.1.1. Consistency. Semantic-based ontology reasoners (e.g., HermiT [66], Pellet [67], ELK [68], and FACT++ [69]) are commonly used to evaluate ontology consistency. They infer the inconsistency of the logical sequence of ontology contents (e.g., terms and their interconnectedness) [29]. Among commonly accepted reasoners, HermiT and Pellet are available in Protégé and support analysis for complex ontology like VHBIEO. There is no significant difference in performance between those reasoners [70]. For cross-checking, the authors used both reasoners to investigate the consistency of VHBIEO. The reasoners did not declare errors about the consistency.

3.3.1.2. Completeness. Completeness measured whether the domain of virtual human-building interaction experimentation is appropriately described by VHBIEO [71]. It included measures of completeness with regards to the language (i.e., everything in VHBIEO could be described by using the given language), the domain (i.e., VHBIEO adequately provided terms and structures describing relevant concepts in the domain), and application requirements (i.e., VHBIEO provided sufficient supports for describing applications) [71]. The completeness respecting the language was measured by affirming that terms in VHBIEO were described in computer-readable language. For the completeness associated with the domain, all important terms were included in VHBIEO and aligned with the needs of the virtual human-building interaction experimentation. Furthermore, VHBIEO involved the internal structure (i.e., the ontology base and ontological commitment) and APV affirming that it sufficiently provided support for describing applications.

3.3.1.3. Redundancy. Redundancy occurs when existing terms are redefined or inferred by other terms. Two judgments affirmed no redundancy occurring in VHBIEO, namely 1) all terms in VHBIEO included their individual concept, and 2) no identical terms appeared among classes in VHBIEO.

3.3.2. *Application*

The purposes of application evaluations are to demonstrate that VHBIEO can describe experimentations, promote machine-readable, accessible, and processable information, and incorporate unique information using APV.

3.3.2.1. Application cases. The experimentations relevant to Chokwitthaya et al. [59], Saeidi et al. [43], and Rentala et al. [65] were standardized and described using VHBIEO. Their data files were generated and published on Dataverse, a web-based data repository, which can be retrieved via https://doi.org/10.7910/DVN/3MR1PV, https://doi.org/10.7910/DVN/YCTE7O, and https://doi.org/10.7910/DVN/LCJ6RO, respectively.

Chokwitthaya et al. [59] simulated a single-occupancy office in IVE to observe participants’ lighting interactions. They used a survey to gather the likelihood of switching a light on under 48 events associated with the work plane illuminance levels, office tasks, and accessibility of a switch. The experiment was entirely conducted in IVE and implemented fundamental elements of virtual human-building interaction experimentation, such as variables, plans (e.g., contexts, predictor conditions, events, states, and actions), building, virtual reality tools, a survey question, and units. Such elements are commonly involved in virtual human-building interaction experiments. Thereby, the information from the experiment provided an opportunity to evaluate the ability of VHBIEO to standardize common experimental elements. In addition, to generate the data file, the general and virtual commitments were implemented, which benefitted the evaluation of Lexons and rules associated with the commitments. More specifically, it tested the validity and appropriateness of the internal structure of VHBIEO with respect to supporting the description of such information. The success of generating the data file offered confidence in applying VHBIEO to standardize experimentations and handle more complex information.

Saeidi et al. [43] performed an experiment to study participants lighting interactions in a virtually single-occupancy office. They simulated several sequential events based on the time of the day (a total of 36 days and four events in a day). They used work plane illuminance as a

```
PREFIX expo: <http://www.hozo.jp/owl/EXPOApr19/>
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
PREFIX vhbieo: <https://w3id.org/vhbieo#>
SELECT ?class ?individual ?property ?value ?controlledvalue
WHERE {
      ?class rdfs:subClassOf* expo:Variable .
      ?individual rdf:type ?class .
      ?individual ?property ?value .
      optional {?value vhbieo:controlled_value ?controlledvalue}}
```

(a)

Class	Individual	Property	Value	Controlled Value
Target Variable	TAV000001	label	likelihood of switching the light on	-
Controlled Contextual Variable	CCV000001	label	Office task	-
		defineContext	CTX000001	reading
		defineContext	CTX000002	relaxing
		defineContext	CTX000003	meeting
		defineContext	CTX000004	drawing
	CCV000002	label	accessibility of light switch	-
		defineContext	CTX000005	light switch is…
		defineContext	CTX000006	light switch is…
Predictor Variable	PDV000001	label	work area illuminance	-
		hasUnitOf	lux	-
		hasControlledCondition	PDC000001	50
		hasControlledCondition	PDC000002	100
		hasControlledCondition	PDC000003	150
		hasControlledCondition	PDC000004	200
		hasControlledCondition	PDC000005	350
		hasControlledCondition	PDC000006	500

(b)

```
PREFIXexpo: <http://www.hozo.jp/owl/EXPOApr19/>
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
PREFIX vhbieo: <https://w3id.org/vhbieo#>
SELECT ?class ?individual ?property ?value
    WHERE {
    ?class rdfs:subClassOf* expo:PlanOfExperimentalActions .
    ?individual rdf:type ?class .
    ?individual ?property ?value .}
```

(c)

Class	Individual	Property	Value
Actions	ACT000001	label	selecting likelihood of switching the light on
LightID	LID	lable	light ID 000001
		hasState	STA000000
Context	CTX000001	isContextOf	CCV000001
		controlled_value	reading
	…	…	…
Predictor Condition	PDC000001	isConditionOf	PDV000001
		controlled_value	50
	…	…	…
Event	EVE000001	compriseOf	CTX000001
		compriseOf	CTX000005
		compriseOf	PDC000001
	…	…	…

(d)

```
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
PREFIX sosa: <http://www.w3.org/ns/sosa/>
SELECT ?individual ?property ?value ?label
WHERE {
      ?individual a sur:CompleteQuestion .
      ?individual ?property ?value .
      optional {?value rdfs:label ?label}}
```

(e)

Individual	Property	Value	Label
CMQ000101	type	CompleteQuestion	-
	actsOnProperty	TAV000001	likelihood of switching light on
	answerTo	MCQ000001	how likely are you going to turn on the light?
	respondToEvent	EVE000001	-
	associatedWithBuild	BID000001	-
	isDataOf	OCC000001	ALI
	hasSimpleResult	99.0	-
CMQ000102	type	CompleteQuestion	-
	actsOnproperty	TAV000001	probability of switching on
	answerTo	MCQ000001	how likely are you going to turn on the light?
	respondToEvent	EVE000002	-
	associatedWithBuild	BID000001	-
	isDataOf	OCC000001	ALI
	hasSimpleResult	0.75	-
…	…	…	…

(f)

Fig. 7. Examples of queries for finding information in the experiment performed in Chokwitthaya et al. [59] and their results.

predictor variable, and occupancies, length of leaving, and the time of a day as controlled contextual variables. Auditory and visual cues were used to guide a participant. The participant was required to interact with the light switch to satisfy visual comfort under different events. A virtual actuation collected the results of the light-switching interactions. The standardization of the experiment was challenging since the experiment involved complex components such as the sequential events, cues, and virtual actuation. The case was selected to evaluate the ability of VHBIEO to handle the description of such components. Lexons and rules associated with the general and virtual commitments were further proven to support complex experimental information.

Rentala et al. [65] used a mixed reality (i.e., a combination of a climate chamber and VR) to validate participants' thermal sensation in IVE. They exposed participants to several events associated with room temperature, thermal exposures (i.e., heat and cold exposures), and experimental settings (i.e., in-situ and IVE). The participants answer surveys regarding thermal sensation, acceptability, and comfort. In each event, skin temperature, heart rate, and RR interval data were collected. The case allows a more comprehensive evaluation of VHBIEO for describing the experimental information. Since the experiment involved in-situ and virtual reality, the data file was generated using all commitments. Therefore, the majority of Lexons and rules defined in VHBIEO were evaluated. In addition, the case needed to include 7-point Likert scales, which were uniquely used in the experiment. It enabled the evaluation of APV for allowing the inclusion of the scales.

3.3.2.2. Promoting Machine-Readable, Accessible, and processible data files (Answer to CQ 14). The ability of the machine to query information in the data file is a common technique used to prove whether an ontology supports machine-readable and accessible data files [72,74]. Therefore, the section illustrates several queries of data files standardized by VHBIEO via standardized query language (SPARQL).

Several queries successfully obtained information about the experiment performed by Chokwitthaya et al. [59], as shown in Fig. 7. Fig. 7a shows queries relevant to variables. According to the results in Fig. 7b, the experiment involved target (i.e., likelihood of switching the light on), controlled contextual (i.e., office tasks and accessibility of light switch), and predictor (i.e., work plane illuminance) variables. Each variable had unit. Controlled contextual variables defined contexts and predictor variables had controlled conditions. The experimental plan was queried (Fig. 7c). The results contained information on actions that participants were allowed to perform in the experiment, Light ID and its state, contexts, predictor conditions, and events (Fig. 7d). Actions were selecting the likelihood of switching the light on. Contexts and Predictor conditions comprised multiple controlled values related to office tasks and accessibility of light switches, and work plane illuminance, respectively. Fig. 7e demonstrates that VHBIO allowed querying for experimental results acquired by a survey and their associated components. Fig. 7f shows complete questions describing the selected likelihood of switching on as simple results. Each of them involved information of target variable, question, occupant ID, event, and

```
PREFIX sosa: http://www.w3.org/ns/sosa/
PREFIX vhbieo: https://w3id.org/vhbieo/
SELECT ?Event (AVG(?Result) AS ?AverageLikelihoodOfSwitchingOn)
WHERE { SELECT DISTINCT ?event ?result
        WHERE { ?individual a sur:CompleteQuestion.
                ?individual vhbieo:respondToEvent ?event .
                ?individual sosa:hasSimpleResult ?result .}}
GROUP BY ?event
```

(a)

Event	Average likelihood of switching the light on
EVE000001	0.90
EVE000002	0.64
…	…
EVE000048	0.27

(b)

Fig. 8. Finding an average of the probability of light switching on in each event (a) and its results (b).

```
PREFIX expo: <http://www.hozo.jp/owl/EXPOApr19/>
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
PREFIX vhbieo: <https://w3id.org/vhbieo#>
PREFIX sted: <https://w3id.org/sted#>
SELECT ?sequence ?event ?value ?type ?controlledvalue ?comment
WHERE {
      ?sequence a vhbieo:Sequence .
      ?sequence ?property ?event .
      filter (?property=vhbieo:hasEvent)
      optional {?event vhbieo:compriseOf ?value .
              ?value rdfs:comment ?comment .
              ?value a ?type .
              filter (?type=sted:Context ||
                     ?type=vhbieo:PredictorCondition)
              ?value vhbieo:controlled_value ?controlledvalue.}}
```

(a)

Sequence	Event	Value	Type	Controlled Value	Comment
SEQ000001	EVE000001	CTX010101	Context	non-occupy	-
		CTX020101	Context	non-leaving	non-leaving
		CTX030101	Context	08:00:00	time of a day
		PDC000003	PredictorCondition	700	work area illuminance
	EVE000002	CTX010201	Context	occupy	-
		CTX020302	Context	long leaving 2	long-leaving
		CTX030102	Context	09:20:00	time of a day
		PDC000003	PredictorCondition	700	work area illuminance
…	…	…	…	…	…

(b)

```
PREFIX expo: <http://www.hozo.jp/owl/EXPOApr19/>
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
PREFIX vhbieo: <https://w3id.org/vhbieo#>
PREFIX sted: <https://w3id.org/sted#>
SELECT ?context ?property ?cue ?label
WHERE {
      ?context a sted:Context .
      ?context ?property ?cue .
      filter (?property=vhbieo:hasCue)
      optional {?cue a ?type.
               ?cue rdfs:label ?label .}}
```

(c)

Context	Property	Cue	Type	Label
CTX020101	hasCue	AUC020101	AuditoryCue	you have arrived at your office
CTX020201	hasCue	AUC020201	AuditoryCue	you are going to get coffee and return quickly to the office
…	…	…	…	…
CTX030109	hasCue	VIC030109	VisualCue	a clock showing 4:00 pm
CTX030110	hasCue	VIC030110	VisualCue	a clock showing 7:30 pm

(d)

```
PREFIX expo: <http://www.hozo.jp/owl/EXPOApr19/>
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
PREFIX vhbieo: <https://w3id.org/vhbieo#>
PREFIX sosa: <http://www.w3.org/ns/sosa/>
PREFIX sted: <https://w3id.org/sted#>
SELECT ?actuation ?property ?value ?label
WHERE {
      ?actuation a sosa:Actuation .
      ?actuation ?property ?value .
      filter (?property=vhbieo:respondToSequence
      ||?property=vhbieo:respondToEvent
      ||?property=vhbieo:currentState
      ||?property=sosa:hasSimpleResult)
      optional {?value rdfs:label ?label}}
```

(e)

Actuation	Property	Value	Label
ATT010101	currentState	STA00102	light on
	respondToEvent	EVE000001	
	respondToSequence	SEQ000001	
	hasSimpleResult	light on	
ATT010102	currentState	STA00102	light on
	respondToEvent	EVE000002	
	respondToSequence	SEQ000001	
	hasSimpleResult	light off	
ATT010103	currentState	STA00101	light off
	respondToEvent	EVE000003	
	respondToSequence	SEQ000001	
	hasSimpleResult	light off	
…	…	…	…

(f)

Fig. 9. Examples of queries for finding information in the experiment performed in Saeidi et al. [43] and their results.

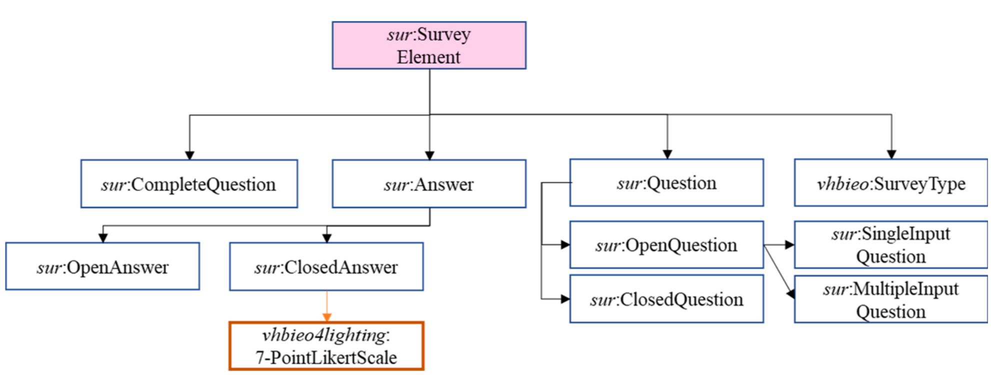

Fig. 10. APV added 7-point Likert scales to VHBIEO at *sur*:SurveyElement.

```
PREFIX vhbieo: <https://w3id.org/vhbieo/>
PREFIX vhbieo4lighting: <http:// w3id.org/vhbieo/vhbieo4thermal>
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
SELECT ?Answer ?Detail ?Property ?Question ?SurveyType
WHERE {
      ?Answer a  vhbieo4thermal:7pointsLikertScale .
      ?Answer ?Property ?value .
      ?Answer vhbieo:AnswerFor ?questionCode .
      ?questionCode rdfs:label ?Question .
      ?questionCode vhbieo:isTypeOf ?surveyType .
      ?surveyType rdfs:label ?SurveyType .
      optional {?Answer rdfs:comment ?Detail}
      filter(?Property = vhbieo:AnswerFor) }
```

(a)

Answer	Detail	Property	Question	SurveyType
7LK000001	Hot (+3) Warm (+2) Slightly Warm (+1) Neutral (0) Slightly Cool (−1) Cool (−2) Cold (−3)	AnswerFor	what is your thermal sensation, at this point in time?	thermal sensation survey
7LK000002	Perfectly Acceptable (+3) Acceptable (+2) Slightly Acceptable (+1) Neutral (0) Slightly Unacceptable (−1) Unacceptable (−2) Totally Unacceptable (−3)	AnswerFor	is the thermal environment, at this point in time, acceptable to you?	thermal acceptability survey
7LK000003	Very Comfortable (+3) Comfortable (+2) Slightly Comfortable (+1) Neutral (0) Slightly Uncomfortable (−1) Uncomfortable (−2) Very Uncomfortable (−3)	AnswerFor	what is your general thermal comfort vote, at this point in time?	thermal comfort survey

(b)

Fig. 11. Query for finding 7-point Likert scales (a) and its results (b).

building relevant to the simple result.

To prove that VHBIEO enhances machine-processable data, an analysis for finding averages of the likelihood of switching on in each event was performed (Fig. 8a). The averages are illustrated in Fig. 8b. Other and more complex analyses could be performed through querying.

Sequential scenarios are common in virtual human-building interaction experiments, especially for simulating longitudinal occurrences such as the sequence of times in days applied in the experiment conducted by Saeidi et al. [43]. The sequence considered four sequential events relevant to the time of day, occupancy, length of leaving, and work area illuminance. Fig. 9a shows a query of the sequences and their relevant components. Fig. 9b illustrates the results of the query, which proves the capability of VHBIEO in handling sequential scenarios. Furthermore, the experiment implemented auditory and visual cues to inform participants about contexts (i.e., times and tasks). Fig. 9c is a query to find information on contexts that have associated cues. Fig. 9d shows the results of the query. In the experiment, there were interconnections between events and states of a light (e.g., light on and off). That is, state$_i$ (initial state) changed to state$_{i+1}$ (state change) by switching the light upon the occurrence of an event, and then, state$_{i+1}$ became state$_i$ of a next adjacent event in a sequence. State$_{i+1}$ might play a role in influencing participants to perform an action in the next event. VHBIEO could support such situation, where the query in Fig. 9e acquires information of the experimental results. Its results in Fig. 9f describe actuations used to store information of the light statuses in events of the sequence. The actuation stored the light status after being switched as the simple result, and manipulated it as the current state of the light in the next event.

3.3.2.3. Inclusion of unique information. An experiment by Rentala et al. [65] used 7-point Likert scales as answer choices for the thermal sensation, acceptability, and comfort questionnaires. Though, VHBIEO did not describe them. To allow the description, APV was implemented by attaching *vhbieo4thermal*:7-pointLikertScale as a subclass of '*sur*:ClosedAnswer' (Fig. 10). Querying the scales and their associated questions are illustrated in Fig. 11a. The result of the query is presented in Fig. 11b, where the list of choices and their properties, associated questions, and the survey type were obtained. The example affirmed the ability of APV in allowing the inclusion of unique information.

4. Discussion

VHBIEO was developed as a domain ontology specifically for virtual human-building interaction experimentation. Ontology development approaches, existing ontologies, and semantic models were adopted to develop VHBIEO. The discussion explores several aspects in accordance with the development to form conclusive remarks, recognizing important details, rationalities, and challenges of developing VHBIEO.

- VHBIEO described key terms and structures for standardizing information of virtual human-building interaction experimentation.
- Competency questions (CQs) represented requirements and were considered as the driver of development. Therefore, CQs must be conscientiously defined. The authors formulated CQs based on the contribution that identifies the purpose, domain, scope, and crucial needs for developing an ontology mentioned in the ontology development approaches. Through those considerations, CQs were adequate to direct the development, and, by answering CQs, the effectiveness of the development was proven.
- The authors reused terms in existing ontologies and semantic models to develop VHBIEO. Extending, inheriting, and reusing ontologies and semantic models are common and highly recommended. Developers can avoid developing ontologies from scratch by extending and inheriting existing ontologies, which potentially reduces the workload. Reusing terms helps developers to avoid defining terms that are redundant and cause confusion.
- Uniform Resource Locator (URL) for VHBIEO was registered as https://w3id.org/vhbieo. The URL played a significant role in allowing machines to reach VHBIEO through the Internet, which made VHBIEO public.
- The internal structure of ontologies determines the interconnectedness and commitment. VHBIEO used the DOGMA methodology to design the structure because it distinguished the structure into two layers, easing the design and understanding of the structure.
- Customization is one of the important features since ontologies may not thoroughly describe all concepts and fit all needs of applications. Hence, VHBIEO provided the application view (APV) approach to support the needs of customizations. Nonetheless, other ontologies may propose other techniques to handle customization.
- Taxonomy evaluation, namely consistency, completeness, and redundancy checks, ensured that VHBIEO did not involve structural errors and logical conflicts. Importantly, it promoted users' confidence in implementing VHBIEO.
- According to the application, information about the experimentations was standardized using VHBIEO. Machines could understand and retrieve information on various components in the experimentations. Moreover, analysis can be performed through computational processes. Such evidence affirmed that VHBIEO effectively provided standardized information, where such information helped to enable machine-readability, accessibility, and processibility.
- The capability of APV to allow the inclusion of unique information was proven in the application. APV is important for reasons. It can lessen limitations and enhance the usability of VHBIEO. It helps narrow down the description to specific information that is not

described by VHBIEO, which contributes to enhancing the completeness of data files.

5. Limitations

Identified limitations are discussed in the following.

- Indeed, ontologies, including VHBIEO, must be continuously maintained and refined (i.e., the maintenance stage) due to causes, such as changes and updates of domain knowledge and enhancement of ontologies' capability [74]. The maintenance stage requires the involvement of further implementation, problem-solving, and expert knowledge to identify maintenance and refinement.
- Some terms newly defined in VHBIEO might already exist in other ontologies and/or semantic models, but the authors did not discover them. If such terms are discovered, the maintainance stages will update VHBIEO accordingly.
- In the future, VR technology may be capable of simulating more complex simulations and covering continuously longitudinal experiments. In such a case, applying STED as the core of VHBIEO may need adjustment.
- In more advanced applications, especially collaborative experiments, the structure of VHBIEO may not support the applications in some aspects. For instance, experiments may be performed collaboratively in different places and phases, where data exchanges and updates carry out during the experiments [75,76]. In the future updates, VHBIEO will consider inclusion of such aspects.
- At this moment, APV allows the description of unique terminologies and concepts for specific experiments. VHBIEO does not provide support for other features, such as customization of the internal structure, and automating, mapping, and bridging with other ontologies [77]. The features are needed to enhance the capability of VHBIEO.
- As recommended in NeOn [24], various aspects of the technical quality of an ontology (e.g., applications and feedbacks from stakeholders) should be considered to evaluate VHBIEO. In this work, the application aspect was acknowledged. However, limited applications were used at the current stage and more applications are needed for evaluatation and further improvement of VHBIEO. Feedback from stakeholders was excluded from the current work. Stakeholder evaluations are expected to perform during the maintenance stages.

6. Conclusion and future works

Tthe authors developed Virtual Human-Building Experiment Ontology (VHBIEO) to standardize virtual human-building interaction experimentation. It is an ontology extending EXPO at the domain level. It reused terms from the existing ontologies and semantic models (e.g., STED, DNAs, ifcOWL, SSN, SUR, UO) and implemented the DOGMA methodology to establish the internal structure. Competency questions (CQs) were defined to elicit the requirements of the development. During the development, VHBIEO answered CQs thoroughly, proving the effectiveness of the development and VHBIEO itself. In addition, the application view (APV) approach was applied to allow the inclusion of unique information. The evaluations proved no occurences of taxonomy errors and affirmed the technical quality of VHBIEO.

Yet, VHBIEO is in its initial stage. In fact, an ontology involves several rounds of maintenance, refinement, alignment, and refactoring throughout its life cycle (i.e., maintenance stages). During maintenance stages, VHBIEO may need revisions, where some concepts and terminologies may be added and/or removed, parts of the structure may be revised, and rules may be changed. The maintenance stages require further implementation, problem-solving, and expert knowledge to improve VHBIEO. The authors plan to address those aspects in future iterations of VHBIEO.

Appendix 1
Rules in the ontological commitments.

RuleID	Rule Definition	Commitment
1	Visible Lexons to this commitment are {Lno. 1, 2, 7, 8, 13 – 18, 23, 26, 27, 32 – 42, 45, 48 – 53, 56, 59 – 64}	General commitment
2	*vhbieo*:ExperimentalProtocol must at least *vhbieo*:specifyBuilding one *vhbieo*:BuildingID *vhbieo*:defineVariable one *vhbieo*:PredictorVariable and one *expo*:TargetVariable	
3	It is allowed several *ssn*:Observation, *ssn*:Actuation, and *sur*:CompleteQuestion *vhbieo*:isDataOf the same *dnas*:Occupant-ID.	
4	The possible simpleResult of *ssn*:Observation, *ssn*:Actuation, and *sur*:CompleteQuestion are string, integer, and float.	
5	The possible controlledValue of *vhbieo*:PredictorCondition and *sted*:Context are string, integer, and float.	
6	Visible Lexons to this commitment are {LNo. 4, 6, 10, 12, 20, 22, 25, 29, 43, 44, 54, 55}	In-situ commitment
7	*vhbieo*:ExperimentalProtocol must at least *vhbieo*:specifyHardwareType one *vhbieo*:In-situHardware *vhbieo*:set one *vhbieo*:In-situSetting	
8	*vhbieo*: In-situSetting must be *vhbieo*:assembledThrough *vhbieo*:In-situHardware.	
9	All buildings (represented by *vhbieo*:BuildingID) must be *vhbieo*:simulatedIn *vhbieo*:In-situSetting.	
10	*dnas*:Actions must be *vhbieo*:performedThrough *vhbieo*:In-situHardware and is either *vhbieo*:capturedBySensor *ssn*:Sensor, *vhbieo*:capturedByActuator *ssn*:Actuator, or *vhbieo*:capturedByQuestion *sur*:Question.	
11	One *vhbieo*:In-situSetting can *vhbieo*:enableControlOf several *vhbieo*:Controlled ContextualVariable and/or *vhbieo*:PredictorCondition.	
12	One *vhbieo*:In-situSetting can *vhbieo*:enableOccurrenceOf several *vhbieo*:UncontrolledContextualVariable.	
13	*vhbieo*:UncontrolledContextualVarible is either *vhbieo*:capturedBySensor *ssn*:Sensor, *vhbieo*:capturedByActuator *ssn*:Actuator, or *vhbieo*:capturedByQuestion *sur*:Question.	
14	Visible Lexons to this commitment are {LNo. 3, 5, 9, 11, 19, 21, 24, 28, 46, 47, 57, 58}	Virtual commitment
15	*vhbieo*:ExperimentalProtocol must at least *vhbieo*:specifyHardwareType one *vhbieo*:VirtualReality *vhbieo*:set one *vhbieo*:VirtualSetting	
16	*vhbieo*: VirtualSetting must be *vhbieo*:assembledThrough *vhbieo*:VirtualReality.	
17	All buildings (represented by *vhbieo*:BuildingID) must be *vhbieo*:simulatedIn *vhbieo*:VirtualSetting.	
18	*dnas*:Actions must be *vhbieo*:performedThrough *vhbieo*:VirtualReality and is either *vhbieo*:capturedBySensor *vhbieo*:VirtualSensor, *vhbieo*:capturedByActuator *vhbieo*:VirtualActuator, or *vhbieo*:capturedByQuestion *sur*:Question.	
19	One *vhbieo*:VirtualSetting can *vhbieo*:enableControlOf several *vhbieo*:Controlled ContextualVariable and/or *vhbieo*:PredictorCondition.	
20	One *vhbieo*:VirtualSetting can *vhbieo*:enableOccurrenceOf several *vhbieo*:UncontrolledContextualVariable.	
21	*vhbieo*:UncontrolledContextualVarible is either *vhbieo*:capturedBySensor *vhbieo*:VitualSensor, *vhbieo*:capturedByActuator *vhbieo*:VitualActuator, or *vhbieo*:capturedByQuestion *sur*:Question.	

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

'Yimin Zhu reports financial support was provided by National Science Foundation. Weizhuo Lu reports financial support was provided by Kempestiftelserna Foundations and the Swedish Energy Agency.'

Data availability

Data will be made available on request.

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Appendix

References

[1] J.M. Davila Delgado, L. Oyedele, P. Demian, T. Beach, A research agenda for augmented and virtual reality in architecture, engineering and construction, Adv. Eng. Informatics. 45 (December 2019) (2020) 101122, doi: 10.1016/j.aei.2020.101122.

[2] C. Chokwitthaya, R. Dibiano, S. Saeidi, S. Mukhopadhyay, Y. Zhu, Enhancing the prediction of artificial lighting control behavior using virtual reality (VR): a pilot study, Constr. Res. Congress (2018) 216–233, https://doi.org/10.1061/9780784481301.022.

[3] Y. Zhu, S. Saeidi, T. Rizzuto, A. Roetzel, R. Kooima, Potential and challenges of immersive virtual environments for occupant energy behavior modeling and validation: a literature review, J. Build. Eng. 19 (2018), https://doi.org/10.1016/j.jobe.2018.05.017.

[4] S. Saeidi, G. Rentala, T. Rizzuto, T. Hong, N. Johannsen, Y. Zhu, Exploring thermal state in mixed immersive virtual environments, J. Build. Eng. 44 (June) (2021), 102918, https://doi.org/10.1016/j.jobe.2021.102918.

[5] G. Ozcelik, B. Becerik-Gerber, Benchmarking thermoception in virtual environments to physical environments for understanding human-building interactions, Adv. Eng. Inf. 36 (April) (2018) 254–263, https://doi.org/10.1016/j.aei.2018.04.008.

[6] S. Norouziasl, A. Jafari, Y. Zhu, Modeling and simulation of energy-related human-building interaction: a systematic review, J. Build. Eng. 44 (June) (2021), 102928, https://doi.org/10.1016/j.jobe.2021.102928.

[7] F. Zhang, Z. Xu, Y. Yang, M. Qi, H. Zhang, Virtual reality-based evaluation of indoor earthquake safety actions for occupants, Adv. Eng. Inf. 49 (2021), 101351, https://doi.org/10.1016/j.aei.2021.101351.

[8] C. Chokwitthaya, Y. Zhu, R. Dibiano, S. Mukhopadhyay, Combining context-aware design-specific data and building performance models to improve building performance predictions during design, Autom. Constr. 107 (2019), 102917, https://doi.org/10.1016/j.autcon.2019.102917.

[9] Y. Yan, K. Chen, Y. Xie, Y. Song, Y. Liu, The effects of weight on comfort of virtual reality devices, in: International Conference on Applied Human Factors and Ergonomics, 2018, pp. 239–248, doi: 10.1007/978-3-319-94706-8_27.

[10] N. Li, M. Asce, J. Du, M. Asce, V.A. González, M. Asce, J. Chen, S.M. Asce, Methodology for extended reality – enabled experimental research in construction engineering and management, 148 (10) (2022) 1–16, doi: 10.1061/(ASCE) CO.1943-7862.0002367.

[11] S. Gilani, C. Quinn, J.J. McArthur, A review of ontologies within the domain of smart and ongoing commissioning, Build. Environ. 182 (July) (2020), 107099, https://doi.org/10.1016/j.buildenv.2020.107099.

[12] D.Y. Lee, H. lin Chi, J. Wang, X. Wang, C.S. Park, A linked data system framework for sharing construction defect information using ontologies and BIM environments, Automation Construction 68 (2016) 102–113, doi: 10.1016/j.autcon.2016.05.003.

[13] Y. Kitamura, M. Kashiwase, M. Fuse, R. Mizoguchi, Deployment of an ontological framework of functional design knowledge, Adv. Eng. Inf. 18 (2) (2004) 115–127, https://doi.org/10.1016/j.aei.2004.09.002.

[14] T. Elsaleh, M. Bermudez-Edo, S. Enshaeifar, S.T. Acton, R. Rezvani, P. Barnaghi, IoT-stream: a lightweight ontology for internet of things data streams, in: Global IoT Summit, GIoTS 2019 - Proceedings, 2019, pp. 1–6, doi: 10.1109/GIOTS.2019.8766367.

[15] B. Butzin, F. Golatowski, D. Timmermann, A survey on information modeling and ontologies in building automation, in: Proceedings IECON 2017 - 43rd Annual Conference of the IEEE Industrial Electronics Society, vol. 2017-Janua, 2017, pp. 8615–8621, doi: 10.1109/IECON.2017.8217514.

[16] J. Ploennigs and A. Schumann, "From semantic models to cognitive buildings," *31st AAAI Conference on Artificial Intelligence, AAAI 2017*, 2017, pp. 5105–5106, doi: 10.1609/aaai.v31i1.10539.

[17] P. Delgoshaei, M. Heidarinejad, M.A. Austin, Combined ontology-driven and machine learning approach to monitoring of building energy consumption, in: ASHRAE and IBPSA-USA Building Simulation Conference, no. October, 2018, pp. 667–674.

[18] H. Dibowski, J. Vass, O. Holub, J. Rojicek, Automatic setup of fault detection algorithms in building and home automation, in: IEEE International Conference on Emerging Technologies and Factory Automation, ETFA, vol. 2016-Novem, 2016, doi: 10.1109/ETFA.2016.7733622.

[19] E. Park, S. Park, S. Stratbücker, An ontology-based approach for building automation data analysis, 2022, pp. 1–8.

[20] H. Pruvost, A. Wilde, O. Enge-Rosenblatt, Ontology-based expert system for automated monitoring of building energy systems, J. Comput. Civ. Eng. 37 (1) (2023) 1–11, https://doi.org/10.1061/(asce)cp.1943-5487.0001065.

[21] M. Uschold, M. Gruninger, Ontologies: principles, methods and applications, Knowledge Eng. Rev. 11 (2) (1996) 93–136.

[22] M. Ferndndez, A. Gmez-p, N. Juristo, METHONTOLOGY: From Ontological Art Towards Ontological Engineering, 1997, pp. 33–40.

[23] N.F. Noy, D.L. McGuinness, Ontology Development 101: A Guide to Creating Your First Ontology, 2001.

[24] M.C. Suárez-Figueroa, A. Gómez-Pérez, E. Motta, A. Gangemi, Ontology Engineering in a Networked World, first ed., Springer, Berlin, Heidelberg, 2012.

[25] L.N. Soldatova, R.D. King, An ontology of scientific experiments, J. R. Soc. Interface 3 (11) (2006) 795–803, https://doi.org/10.1098/rsif.2006.0134.

[26] M. Jarrar, R. Meersman, Ontology engineering -the DOGMA approach, Adv. Web Semantics (2008) 7–34.

[27] Z. Zhou, Y.M. Goh, Q. Li, Overview and analysis of safety management studies in the construction industry, Saf. Sci. 72 (2015) 337–350, https://doi.org/10.1016/j.ssci.2014.10.006.

[28] S. Saad, N. Salim, H. Zainal, Z. Muda, A process for building domain ontology: An experience in developing Solat ontology, in: Proceedings of the 2011 International Conference on Electrical Engineering and Informatics, 2011, no. July, pp. 1–5, doi: 10.1109/ICEEI.2011.6021572.

[29] A. Freitas, R. Vieira, An ontology for guiding performance testing, in: Proceedings - 2014 IEEE/WIC/ACM International Joint Conference on Web Intelligence and Intelligent Agent Technology - Workshops, WI-IAT 2014, vol. 1, 2014, pp. 400–407, doi: 10.1109/WI-IAT.2014.62.

[30] J.A.P. Amorocho, T. Hartmann, Reno-Inst: an ontology to support renovation projects planning and renovation products installation, Adv. Eng. Inf. 50 (August) (2021), 101415, https://doi.org/10.1016/j.aei.2021.101415.

[31] D.L. Mcguinness, Ontologies come of age, in: MIT press Cambridge, MIT press Cambridge, 2001, pp. 174–194.

[32] J. Hietanen, IFC model view definition format, 2008. Available from: <https://e1bd58d2-a-62cb3a1a-s-sites.googlegroups.com/site/objectm3/project-updates/idmifdedaehae/MVD_Format_V2_Proposal_080128.pdf?attachauth=ANoY7cqC2YevcMKdK7EOXFwKS6SFwtia-2Uur00H58uQbIgc2lsnfOU-aV5Jf6NL2saMpnAT2dXwj_AXsSo2yU7ZUv7GkYlU4MAEk9timKHqw2AtZ>.

[33] R. Marmo, F. Polverino, M. Nicolella, A. Tibaut, Building performance and maintenance information model based on IFC schema, Autom. Constr. 118 (May) (2020), 103275, https://doi.org/10.1016/j.autcon.2020.103275.

[34] M.A. Musen, The Protégé project: A look back and a look forward, in: AI Matters. Association of Computing Machinery Specific Interest Group in Artificial Intelligence, vol. 1, no. 4, 2015, doi: 10.1145/2557001.25757003.

[35] M. Shahinmoghadam, W. Natephra, A. Motamedi, BIM- and IoT-based virtual reality tool for real-time thermal comfort assessment in building enclosures, Build. Environ. 199 (April) (2021), 107905, https://doi.org/10.1016/j.buildenv.2021.107905.

[36] O. Baus, S. Bouchard, Moving from virtual reality exposure-based therapy to augmented reality exposure-based therapy: A review, Front. Hum. Neurosci. 8 (MAR) (2014), https://doi.org/10.3389/fnhum.2014.00112.

[37] B. Serrano, R.M. Baños, C. Botella, Virtual reality and stimulation of touch and smell for inducing relaxation: a randomized controlled trial, Comput. Hum. Behav. 55 (2016) 1–8, https://doi.org/10.1016/j.chb.2015.08.007.

[38] A.-S. Dris, F. Lehericey, V. Gouranton, B. Arnaldi, OpenBIM based IVE ontology: an ontological approach to improve interoperability for virtual reality applications, in: Advances in Informatics and Computing in Civil and Construction Engineering, 2019, pp. 129–136, doi: 10.1007/978-3-030-00220-6_16.

[39] A. Heydarian, J.P. Carneiro, D. Gerber, B. Becerik-Gerber, Immersive virtual environments, understanding the impact of design features and occupant choice upon lighting for building performance, Build. Environ. 89 (2015) 217–228, https://doi.org/10.1016/j.buildenv.2015.02.038.

[40] J. Zhang, X. Xia, R. Liu, N. Li, Enhancing human indoor cognitive map development and wayfinding performance with immersive augmented reality-based navigation systems, Adv. Eng. Inf. 50 (October) (2021), 101432, https://doi.org/10.1016/j.aei.2021.101432.

[41] D. Yeom, J.H. Choi, Y. Zhu, Investigation of physiological differences between immersive virtual environment and indoor environment in a building, Indoor Built Environ. 28 (1) (2019) 46–62, https://doi.org/10.1177/1420326X17731945.

[42] X. Li, J. Ling, Y. Shen, T. Lu, S. Feng, H. Zhu, The impact of CCT on driving safety in the normal and accident situation: a VR-based experimental study, Adv. Eng. Inf. 50 (August) (2021), 101379, https://doi.org/10.1016/j.aei.2021.101379.

[43] S. Saeidi, C. Chokwitthaya, Y. Zhu, M. Sun, Spatial-temporal event-driven modeling for occupant behavior studies using immersive virtual environments, Autom. Constr. 94 (2018) 371–382, https://doi.org/10.1016/j.autcon.2018.07.019.
[44] S. Mukhopadhyay, Q. Liu, E. Collier, Y. Zhu, R. Gudishala, Context-Aware Design of Cyber-Physical Human Systems (CPHS), in: International Conference on Communication Systems & Networks (COMSNETS), 2022, pp. 322–329.
[45] C. Chokwitthaya, Y. Zhu, R. Dibiano, M. Supratik, A machine learning algorithm to improve building performance modeling during design, MethodsX 7 (2020) 35–49, https://doi.org/10.1016/j.mex.2019.10.037.
[46] C. Chokwitthaya, E. Collier, Y. Zhu, S. Mukhopadhyay, Improving prediction accuracy in building performance models using generative adversarial networks (GANs), in: International Joint Conference on Neural Networks, 2019, pp. 1–9, doi: 10.1109/IJCNN.2019.8852411.
[47] P.L. Whetzel, H. Parkinson, H.C. Causton, L. Fan, J. Fostel, G. Fragoso, L. Game, M. Heiskanen, N. Morrison, P. Rocca-Serra, S.A. Sansone, C. Taylor, J. White, C. J. Stoeckert, The MGED Ontology: a resource for semantics-based description of microarray experiments, Bioinformatics 22 (7) (2006) 866–873, https://doi.org/10.1093/bioinformatics/btl005.
[48] S.A. Sansone, D. Schober, H.J. Atherton, O. Fiehn, H. Jenkins, P. Rocca-Serra, D. V. Rubtsov, I. Spasic, L. Soldatova, C. Taylor, A. Tseng, M.R. Viant, Metabolomics standards initiative: ontology working group work in progress, Metabolomics 3 (3) (2007) 249–256, https://doi.org/10.1007/s11306-007-0069-z.
[49] P.L. Whetzel, R.A. Brinkman, H.C. Causton, L. Fan, D. Field, J. Fostel, G. Fragoso, T. Gray, M. Heiskanen, T. Hernandez-Boussard, N. Morrison, H. Parkinson, P. Rocca-Serra, S.A. Sansone, D. Schober, B. Smith, R. Stevens, C.J. Stoeckert, C. Taylor, J. White, A. Wood, Development of FuGO: An ontology for functional genomics investigations, OMICS 10 (2) (2006) 199–204, https://doi.org/10.1089/omi.2006.10.199.
[50] T. Hong, S. D'Oca, S.C. Taylor-Lange, W.J.N. Turner, Y. Chen, S.P. Corgnati, An ontology to represent energy-related occupant behavior in buildings. Part II: Implementation of the DNAS framework using an XML schema, Build. Environ. 94 (2015) 196–205, https://doi.org/10.1016/j.buildenv.2015.08.006.
[51] T. Hong, S. D'Oca, W.J.N. Turner, S.C. Taylor-lange, An ontology to represent energy-related occupant behavior in buildings. Part I: Introduction to the DNAs framework, Build. Environ. 92 (2015) 764–777, https://doi.org/10.1016/j.buildenv.2015.02.019.
[52] P. Pauwels, W. Terkaj, ifcOWL ontology, standards.buildingsmart.org, 2019. Available from: <https://standards.buildingsmart.org/IFC/DEV/IFC4/ADD2_TC1/OWL/index.html> (Accessed date: November 20, 2022).
[53] A. Haller, K. Janowicz, S. Cox, D. Le Phuoc, K. Taylor, M. Lefrancois, Semantic Sensor Network Ontology, 2017. Available from: <https://www.w3.org/TR/vocab-ssn/> (Accessed date: October 07, 2021).
[54] D. Scandolari, G.R.C. Calegari, C. Irene, M. Scrocca, The Survey Ontology, 2021. Available from: <https://cefriel.github.io/survey-ontology/docs/index.html>.
[55] G.V. Gkoutos, P.N. Schofield, R. Hoehndorf, The Units Ontology: a tool for integrating units of measurement in science, J. Biol. Databases Curation 2012 (2012) 1–7, https://doi.org/10.1093/database/bas033.
[56] BuildingSMARTInternational, "BuildingSMART — international home of openBIM." www. buildingsmart.com (Accessed date: November 20, 2022).
[57] P. Pauwels, W. Terkaj, EXPRESS to OWL for construction industry: Towards a recommendable and usable ifcOWL ontology, Autom. Constr. 63 (2016) 100–133, https://doi.org/10.1016/j.autcon.2015.12.003.
[58] K. Janowicz, A. Haller, S.J.D. Cox, D. Le Phuoc, M. Lefrançois, SOSA: a lightweight ontology for sensors, observations, samples, and actuators, J. Web Semantics 56 (2019) 1–10, https://doi.org/10.1016/j.websem.2018.06.003.
[59] C. Chokwitthaya, Y. Zhu, S. Mukhopadhyay, E. Collier, Augmenting building performance predictions during design using generative adversarial networks and immersive virtual environments, Autom. Constr. 119 (2020), 103350, https://doi.org/10.1016/j.autcon.2020.103350.
[60] R. Hartson, P.S. Pyla, Agile Lifecycle Processes and the Funnel Model of Agile UX, second ed., Morgan Kaufmann, 2018.
[61] "Industry Foundation Classes 4.0.2.1," *buildingSMART*. Available from: <https://standards.buildingsmart.org/IFC/RELEASE/IFC4/ADD2_TC1/HTML/> (Accessed date: November 28, 2022).
[62] A. Haller, K. Janowicz, S.J.D. Cox, M. Lefrançois, K. Taylor, D. Le Phuoc, J. Lieberman, R. García-Castro, R. Atkinson, C. Stadler, The modular SSN ontology: a joint W3C and OGC standard specifying the semantics of sensors, observations, sampling, and actuation, Semantic Web 10 (1) (2018) 9–32, https://doi.org/10.3233/SW-180320.
[63] C. Chokwitthaya, S. Saeidi, Y. Zhu, R. Kooima, The Impact of Lighting Simulation Discrepancies on Human Visual Perception and Energy Behavior Simulations in Immersive Virtual Environment, in: Congress on Computing in Civil Engineering, Proceedings, vol. 2017-June, 2017.
[64] C. Chokwitthaya, Y. Zhu, S. Mukhopadhyay, Robustness analysis framework for computations associated with building performance models and immersive virtual experiments, Adv. Eng. Inf. 50 (January) (2021), 101401, https://doi.org/10.1016/j.aei.2021.101401.
[65] G. Rentala, Y. Zhu, N.M. Johannsen, Impact of outdoor temperature variations on thermal state in experiments using immersive virtual environment, Sustainability (Switzerland) 13 (19) (2021) pp, https://doi.org/10.3390/su131910638.
[66] B. Glimm, I. Horrocks, B. Motik, G. Stoilos, Z. Wang, HermiT: an OWL 2 Reasoner, J. Autom. Reason. 53 (3) (2014) 245–269, https://doi.org/10.1007/s10817-014-9305-1.
[67] E. Sirin, B. Parsia, B.C. Grau, A. Kalyanpur, Y. Katz, Pellet: a practical OWL-DL reasoner, Web Semantics 5 (2) (2007) 51–53, https://doi.org/10.1016/j.websem.2007.03.004.
[68] Y. Kazakov, M. Krötzsch, F. Simančík, ELK reasoner: architecture and evaluation, in: CEUR Workshop Proceedings, vol. 858, 2012.
[69] D. Tsarkov, I. Horrocks, FaCT++ description logic reasoner: system description, in: The Third international joint conference on Automated Reasoning, 2006, pp. 292–297, doi: 10.1007/11814771_26.
[70] R. Shearer, B. Motik, I. Horrocks, HermiT: A highly-eficient OWL reasoner, in: CEUR Workshop Proceedings, vol. 432, 2009.
[71] D. Vrandečić, Ontologies Evaluation, vol. 16, no. June. 2013, ISBN 13: 3540408347.
[72] A. Wagner, W. Sprenger, C. Maurer, T.E. Kuhn, U. Rüppel, Building product ontology: core ontology for linked building product data, Automation Construction 133 (October 2021) (2022) 103927, doi: 10.1016/j.autcon.2021.103927.
[73] D.L. Nuñez, M. Borsato, OntoProg: an ontology-based model for implementing Prognostics Health Management in mechanical machines, Adv. Eng. Informatics 38 (December 2017) (2018) 746–759, doi: 10.1016/j.aei.2018.10.006.
[74] Z. Sun, C. Hu, C. Li, L. Wu, Domain ontology construction and evaluation for the entire process of software testing, IEEE Access 8 (2020) 205374–205385, https://doi.org/10.1109/ACCESS.2020.3037188.
[75] M. Venugopal, C.M. Eastman, J. Teizer, An ontology-based analysis of the industry foundation class schema for building information model exchanges, Adv. Eng. Inf. 29 (4) (2015) 940–957, https://doi.org/10.1016/j.aei.2015.09.006.
[76] Y.C. Lee, C.M. Eastman, W. Solihin, An ontology-based approach for developing data exchange requirements and model views of building information modeling, Adv. Eng. Inf. 30 (3) (2016) 354–367, https://doi.org/10.1016/j.aei.2016.04.008.
[77] Y. Zheng, S. Törmä, O. Seppänen, A shared ontology suite for digital construction workflow, Autom. Constr. 132 (January) (2021), https://doi.org/10.1016/j.autcon.2021.103930.